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Estimating Diffractive Higgs Boson Production at LHC from HERA Data

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Abstract

Using a recently proposed factorization hypothesis for semi-inclusive hard processes in QCD, one can study, in principle, the diffractive production of the Standard Model Higgs boson at LHC using only, as input, *ep* diffractive hard-processes data of the type recently collected and analyzed by the H1 and ZEUS collaborations at HERA. While waiting for a more precise and complete set of data, we combine here the existing data with a simple Pomeron-exchange picture and find a large spread in the Higgs boson production cross section, depending on the input parametrization of the Pomeron's parton content. In particular, if the Pomeron gluon density $f_{g/\mathbb{P}}(\beta)$ is peaked at large β for small scales, single diffractive events will represent a sizeable fraction of all produced Higgs bosons with an expected better-than-average signal-to-background ratio.

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Searching for the Higgs boson is one of the main goals of future hadron colliders. The main search strategy for this elusive particle rests on the production via the dominant $gg \to H$ fusion process, and on the observation of the subsequent decays into ZZ and ZZ^*, for the mass ranges $m_H > 2m_Z$ and $130\,\mathrm{GeV} < m_H < 2m_Z$, respectively (the experimental signature being four charged leptons from the Z, Z^* decays), or of the rare decay into two photons, $\mathrm{H} \to \gamma\gamma$, for the intermediate mass range $90\,\mathrm{GeV} < m_H < 130\,\mathrm{GeV}$. The search for the Higgs boson in the intermediate mass range is believed to be very difficult [1]. The process $pp \to gg + X \to H + X \to \gamma\gamma + X$ suffers indeed from the large irreducible background $pp \to \gamma\gamma + X$ and from the reducible background $pp \to \mathrm{jet} + \mathrm{jet} + X$, $\mathrm{jet} + \gamma + X$, where the jets fake photons [2,3].

Additional information on the parton-level initial state (i.e. distinguishing gg, qg or $q\overline{q}$ induced processes) in a selected class of Higgs boson production events may help to reduce the background. For instance, the irreducible two-photon background is mainly induced by a quark–antiquark pair and is therefore suppressed if one is able to bias the sample so as to favour initial state gluons (see the brief discussion of backgrounds at the end of the paper). In hard diffractive processes the proton stays essentially intact and its valence quarks go straight into the leading final proton. What recoils against the proton–proton system is naturally expected to be gluon-rich, at least in comparison to unbiased (i.e. diffractive plus non-diffractive) events.

Diffractive hard processes are usually described in the framework of QCD by introducing an effective flux for the exchanged object with vacuum quantum numbers (for short, called the "Pomeron" ($\mathbb{P}$) in the sequel) and by parametrizing the parton densities of the Pomeron itself [4]. There is some experimental evidence in support of the theoretical expectation that the Pomeron is a gluon-rich object [5,6,7]. Tagging leading protons with a large momentum [8], or observing gaps in rapidity as an experimental sign for diffractive processes, may allow to exploit additional information about the hard scattering process and to enrich the sample of gluon-initiated events.

In this paper we study the production of the Standard Model Higgs boson in hard diffractive processes at LHC, using experimental fits to the Pomeron parton densities from groups working at HERA. We point out, however, that, for a study of hard diffractive events, this (partly model dependent) theoretical framework is not really needed. A direct parametrization of the gluon content of a proton fragmenting into a leading proton would be sufficient and is desirable in order to facilitate forthcoming studies of hard diffraction. The corresponding theoretical framework of *fracture functions* has been developed recently [9,10]. The fracture function $M^i_{p,h}(x, z, Q^2)$ gives the joint probability distribution for an observed hadron h (e.g. a leading proton) with a specific momentum fraction z in the proton fragmentation region, and a parton i (e.g. a gluon) of momentum fraction $x = \beta(1 - z)$ initiating the hard process. The

functions $F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$ introduced in [11,12] are closely related to fracture functions in the same way that $F_2(x, Q^2)$ is related to the usual parton densities. We wish to encourage an experimental analysis in terms of such a direct parametrization and thus independent of the "Pomeron exchange picture" which, being non-perturbative, is beyond present theoretical control.

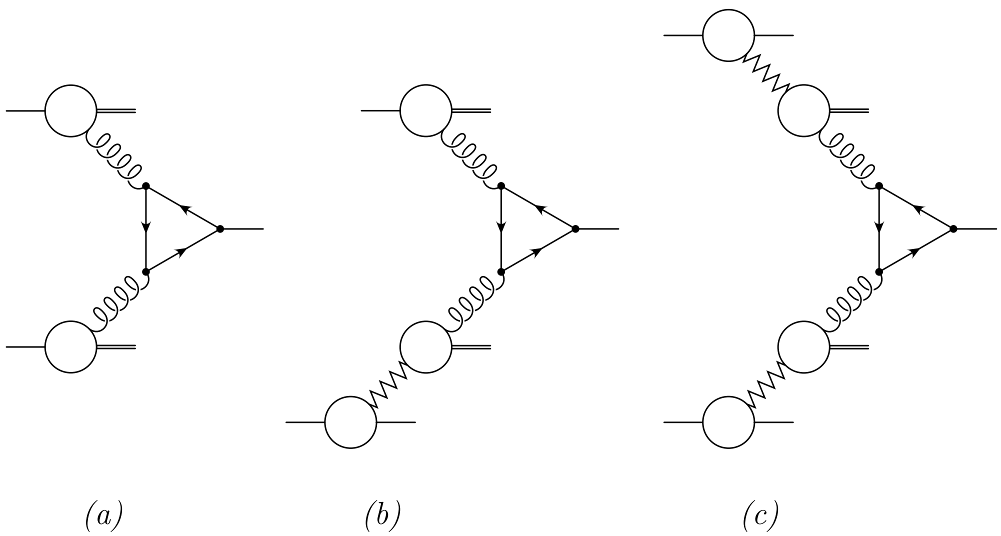


Fig. 1. *Generic diagrams for the total Higgs boson production cross section (a), the single diffractive case (b) and the double diffractive case (c). The quark in the triangle loop is the top quark. Single lines stand for the incident proton and leading outgoing proton, and double lines for the fragments of the proton and Pomeron.*

Figure 1a shows the standard gg fusion graph for Higgs production via a top quark loop, giving the total cross section for $pp \rightarrow gg + X \rightarrow H + X$ in leading order, the process being diffractive or not. Either one or both protons may stay essentially intact, giving rise to single (Fig. 1b) and double (Fig. 1c) diffractive processes. For a soft gluon content of the Pomeron, the double diffractive process has been studied in [13], and the formalism of Regge theory has been applied in [14]. We base our study on the framework for hard diffraction developed in [15], also employed in [13], and do not make use of Regge theory, but instead assume the picture of the Pomeron as an exchanged object carrying vacuum quantum numbers, with a parton content that can be measured and parametrized.

The flux $f_{\mathbb{P}/p}(x_{\mathbb{P}}, t)$ of Pomerons in the proton is given by the parametrization of Donnachie and Landshoff [16,17]. Actually, since the rapidity-gap criterion does not distinguish a leading proton from some other diffractively excited state, $f_{\mathbb{P}/p}$ should be increased relative to the Donnachie–Landshoff value. Equivalently, one can follow the practice of experimental groups to stick to the flux of Refs. [16,17] but allow the overall normalization of the Pomeron's parton densities to exceed the bounds imposed by a naive momentum sum

rule. For the parametrizations of the Pomeron's gluon density [1] we use results from fits by the H1 [6,7] and ZEUS [5,12] collaborations (parametrizations H1a, H1b, H1c and ZEUS [2]) and moreover employ recent results by Gehrmann and Stirling [19] (parametrizations GS1 and GS2). In addition, to facilitate a comparison with [13], we also include two parametrizations with a soft gluon content (parametrizations S and SE, without and with scale evolution, respectively). The parameters of the input distributions are shown in Tab. 1. In the cases where the parametrizations were not available at arbitrary scales, the evolution has been carried out with the standard leading-order Altarelli–Parisi equations with heavy flavour thresholds at the single quark masses [3] and $\Lambda_{\rm QCD} = 200\,\mathrm{MeV}$ for 4 flavours.

Figure 2 shows the various gluon densities and the quark singlet distribution of the Pomeron at a scale of 100 GeV. Two of the H1 parametrizations (H1a and H1c) form a lower and upper bound of all gluon parametrizations considered here; only the ZEUS parametrization is smaller at small values of β. As we will see later on, the Pomeron is probed mainly at large β, and therefore the large spread of the parametrizations of about one order of magnitude translates into a corresponding variation in the calculated cross sections. The quark singlet distribution is better constrained by the $F_2^{D(3)}$ measurement, and so the distributions have a smaller spread at large β, where the present measurements are most sensitive.

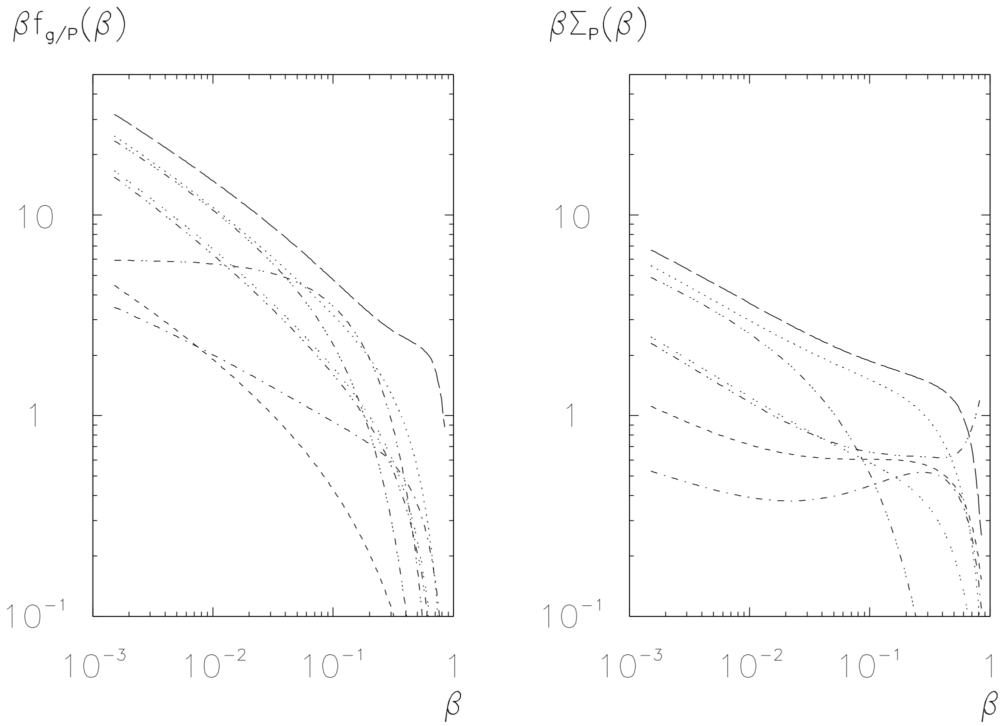
[1] We do not include the model of Buchmüller and Hebecker [18] in our study, although it gives a first principles QCD formulation of diffractive events without employing the concept of the Pomeron, because it is not clear how to define the gluon density for diffractive events in this case. The concepts of "rotation in colour space" and "colour-compensating soft gluon exchange" of this model must probably be applied to the virtual top quark in the triangle loop. Because of *two* incident gluons, there should be an additional constraint related to the colour matching.

[2] The H1 parametrizations are based on fits of $F_2^{D(3)}$, whereas the ZEUS fits also take into account constraints from the photoproduction of jets. In the latter case, if only the information from $F_2^{D(3)}$ is used, it is possible to have a consistent set of parameters with a large gluon content as well. To be definite, we use the central values given in [5].

[3] The evolution for the fit of the parameters in the $F_2^{D(3)}$ analysis of the H1 collaboration has been done with $N_f = 3$ flavours, and by adding charm via the photon–gluon fusion process. In our case, the evolution span is sufficiently large in order to justify the treatment of the charm and bottom quarks as massless flavours. The influence of changing N_f from the values used in our procedure to a fixed number of 3 flavours is to increase the gluon density, because this decreases the number of quark flavours into which the gluon can split. As a result, the cross section for the single diffractive case increases by about 10–20%, and the one for the double diffractive case by about 20–40%.

Table 1
Parametrizations of the Pomeron's parton content. The input distributions are given by $\beta f_{g/\mathbb{P}}(\beta) = A\beta^B(1-\beta)^C$ for the gluon and $\beta f_{q/\mathbb{P}}(\beta) = D\beta^E(1-\beta)^F$ for N_0 light quark flavours q, $\overline{q}$ at the scale μ_0. β is the momentum fraction of the gluon in the Pomeron. We have also included the line types that are used in the plots later on.

		A	B	C	D	E	F	N_0	μ_0
H1a	- - -	0	–	–	0.189	0.351	0.355	3	2 GeV
H1b	···	9.80	1	1	0.416	1	1	3	2 GeV
H1c	— —	60.7	7.99	0.23	0.260	0.782	1.21	3	2 GeV
ZEUS	- · -	2.88	1	1	0.48	1	1	2	7.1 GeV
SE	- ···	6	0	5	0	–	–	–	7.1 GeV
S	- - ··	6	0	5	0	–	–	no evolution	
GS1	·· ··	cf. [19], model 1							
GS2	- ··	cf. [19], model 2							



(a) *(b)*

Fig. 2. *Parametrizations of the Pomeron's gluon density (a) and singlet quark distribution (b). The line types are given in Tab. 1.*

The cross section for Higgs boson production via gg fusion [20] is given by

$$\sigma = \int_{\tau_H}^{1} \frac{\mathrm{d}\xi}{\xi}\, g_1(\xi, \mu^2)\, g_2\left(\frac{\tau_H}{\xi}, \mu^2\right)\, \tau_H\, \sigma_0\left(\frac{m_H^2}{m_{\mathrm{top}}^2}\right). \tag{1}$$

The quantity τ_H is defined by $m_H^2/E_{\rm CM}^2$, where $E_{\rm CM}$ is the centre-of-mass energy of the collider. An explicit expression for the parton-level cross section $\sigma_0(m_H^2/m_{\rm top}^2)$ can be found, e.g., in [21]. For the total cross section and in the single diffractive case, both or one of the $g_i(\xi,\mu^2)$ are the gluon densities $f_{g/p}(\xi,\mu^2)$ of the proton, respectively, which we choose to be the GRV leading-order parametrization [22]. The other g_i's, in the single and double diffractive case, are given by the convolution of the Pomeron flux factor $f_{\mathbb{P}/p}(x_{\mathbb{P}},t)$ and the parton densities of the Pomeron $f_{g/\mathbb{P}}(\beta,\mu^2)$:

$$g_i(\xi,\mu^2) = \int\limits_{-\infty}^{0} \mathrm{d}t \int\limits_{\xi}^{\gamma(\xi,t)} \frac{\mathrm{d}x_{\mathbb{P}}}{x_{\mathbb{P}}}\, f_{\mathbb{P}/p}(x_{\mathbb{P}},t)\, f_{g/\mathbb{P}}\left(\frac{\xi}{x_{\mathbb{P}}},\mu^2\right). \tag{2}$$

The upper limit of the $x_{\mathbb{P}}$-integration is given by the condition that the Pomeron's momentum fraction of the proton does not exceed a certain fraction $x_{\mathbb{P}\rm max}$, in order not to invalidate the parametrization used for the Pomeron flux factor. Moreover, there is a kinematical limit depending on the momentum transfer $t=(p'-p)^2$, where p and p' are the momenta of the incident and outgoing proton, respectively, so that

$$\gamma(\xi,t) = \max\left\{\xi,\ \min\left[x_{\mathbb{P}\rm max}, \frac{-t}{2m_p^2}\left(\sqrt{1+\frac{4m_p^2}{-t}}-1\right)\right]\right\}, \tag{3}$$

m_p being the proton mass. In this expression we have neglected terms of the order of $m_p/E_{\rm CM}$ and $\sqrt{-t}/E_{\rm CM}$, reflecting the ambiguity in the massive case ($m_p \neq 0$, $t \neq 0$) of the definition of the frame-dependent momentum fraction variable $x_{\mathbb{P}}$.

For the numerical evaluation we have chosen $E_{\rm CM} = 10\,\rm TeV$, $m_{\rm top} = 180\,\rm GeV$ and $x_{\mathbb{P}\rm max} = 0.1$. Increasing the centre-of-mass energy to 14 TeV results in an increase of all cross sections by about a factor of 2. The factorization scale μ and the renormalization scale are set to the Higgs boson mass. We use the leading-order running strong coupling constant with $\Lambda_{\rm QCD} = 200\,\rm MeV$ for 4 flavours. The dependence of the cross section on the Higgs boson mass m_H is shown in Fig. 3a for the single diffractive case [4] and in Fig. 3b for the double diffractive case. The shape of the mass dependence for the single diffractive case is similar to the non-diffractive case, although the cross section drops faster for increasing Higgs boson mass. In the mass range of $90\,\rm GeV < m_H < 130\,\rm GeV$, the single diffractive cross section for the H1c parametrization is about 25% of the total cross section, whereas most of the

[4] We have subtracted the double diffractive cross section from the single diffractive one, so what is actually plotted is the contribution where the proton which is modelled by the GRV gluon density does not stay intact.

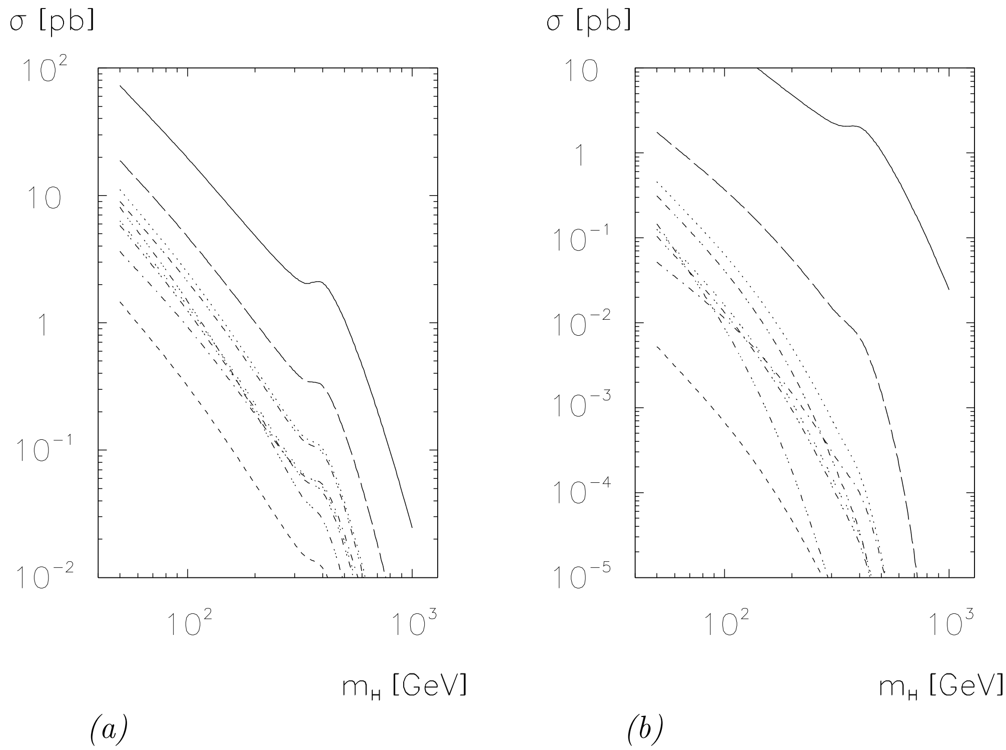


Fig. 3. *Dependence of the single diffractive (a) and double diffractive (b) Higgs boson production cross section on the Higgs boson mass. The full line is the total cross section $pp \to gg+X \to H+X$. The other line types related to various gluon densities of the Pomeron are defined in Tab. 1.*

other parametrizations (excluding H1a) studied here give a fraction of the order of 10%. Except for the H1c parametrization, the double diffractive cross section is very small, less than about 0.1 pb. Varying the gluon content of the ZEUS parametrization within the bounds given in [5] yields a variation of about ±60%. A comparison of the cross sections for the parametrizations S and SE shows that the evolution of the parton densities gives, in the double diffractive case, a large effect; however, this obviously depends on the input scale chosen. It should be noted that the diffractive cross section is not yet well constrained by the measurements of the Pomeron structure function. For $m_H = 100\,\mathrm{GeV}$, the spread is about a factor of 14 in the single diffractive case and about a factor of 600 (!) in the double diffractive case.

Differential distributions for the momentum fraction variables $x_{\mathbb{P}}$, β, $\xi_{\mathbb{P}r} = x_{\mathbb{P}}(1-\beta)$, ξ_{ND} and $\xi_D = x_{\mathbb{P}}\beta$ are shown in Fig 4. Here $\xi_{\mathbb{P}r}$ is the momentum fraction relative to the proton momentum carried by the remnant of the Pomeron, ξ_{ND} is the momentum fraction of the gluon from the fragmenting proton in the single diffractive case and ξ_D is the momentum fraction of the gluon from the Pomeron, relative to the momentum of the incoming proton. The momentum fraction β of the gluon in the Pomeron is large, and the distribution $\beta\,\mathrm{d}\sigma/\mathrm{d}\beta$ peaks at about 0.2. The distribution of the momentum

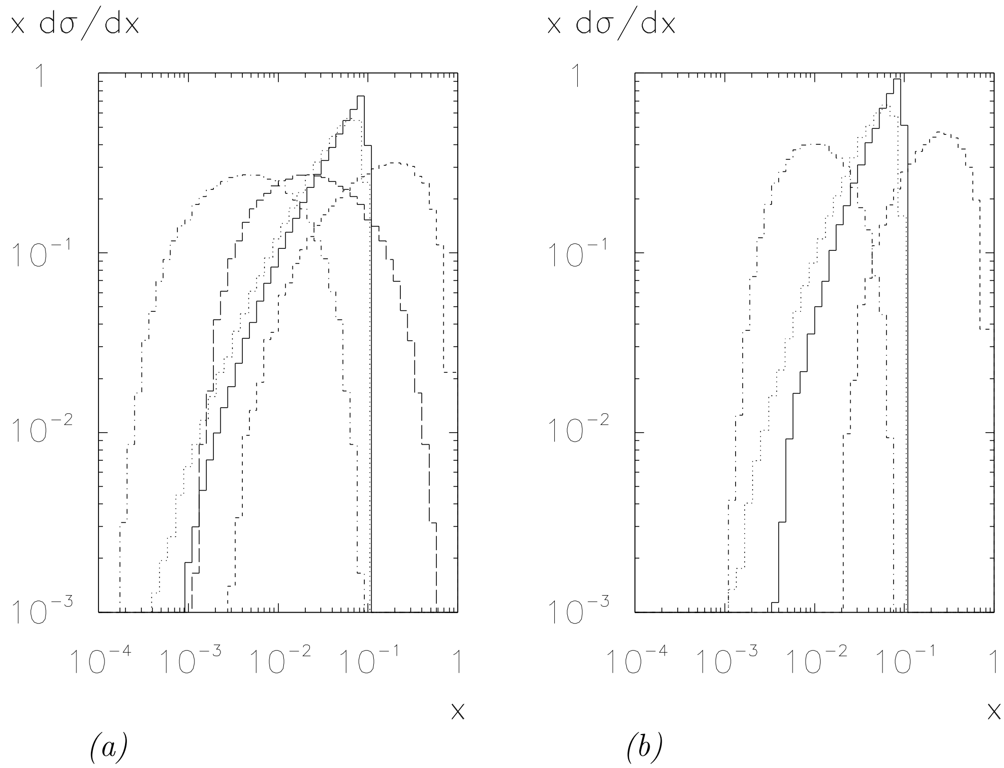


Fig. 4. *Distributions $x\,d\sigma/dx$ for various variables x in the single diffractive (a) and double diffractive (b) case for a Higgs boson mass of* 100 *GeV and the H1b parametrization of the gluon density. The integrated cross section σ is normalized to* 1. *The variable x stands for $x_{\mathbb{P}}$ [——], β [– – –], $x_{\mathbb{P}}(1-\beta)$ [· · ·], ξ_{ND} [— —], ξ_D [– · –]. The ZEUS parametrization gives similar results.*

fraction $x_{\mathbb{P}}$ of the Pomeron in the proton, being cut off by the explicit upper limit $x_{\mathbb{P}\max}$, has large contributions at large $x_{\mathbb{P}}$, although the Pomeron flux behaves like $1/x_{\mathbb{P}}$. The reason for this behaviour is that the invariant mass squared of the produced system in the hard scattering process is fixed and quite large, i.e. $\tau_H = m_H^2/E_{\rm CM}^2 = 10^{-4}$ for $m_H = 100\,$GeV and $E_{\rm CM} = 10\,$TeV. The momentum fraction ξ to be supplied by each of the protons is therefore of the order of 10^{-2} (cf. Fig. 4). Since the gluon density of the Pomeron is decreasing rapidly for increasing β, the Pomeron itself must carry a comparably large fraction of the proton momentum. This fact has the consequence that the momentum fraction $\xi_{\mathbb{P}r}$ carried by the "Pomeron remnant" relative to the proton momentum is, on the average, much larger than 10^{-2}. The rapidity gap which would be observed in principle is between the beam direction and the Pomeron remnant. Assuming naively that the latter is simply a jet with longitudinal momentum $\xi_{\mathbb{P}r}p$ and transverse momentum of the order of the transverse momentum of the scattered proton, multiplied by $(1-\beta)$, then it turns out that the distribution of the pseudorapidity η of this jet peaks at values of the order of $\eta = 7$. This means that hardly any gap will be observable

in real experiments [5], even if fragmentation effects are taken into account [6]. Instead, for diffractive events, under the assumption that the scattered proton escapes detection, the signature will be a comparably small hadronic activity in the forward direction, with the unobserved scattered proton carrying a large momentum fraction [7]. In the double diffractive case, the measurement of the invariant mass of the two-Pomeron system is in principle possible by measuring the energy of the two scattered protons in forward spectrometers [8]. If the Pomerons fragment, then the measurement of the invariant mass of the two-Pomeron system probably gives no constraint on the invariant mass of the two-gluon system, because the gluons carry only a small fraction of the Pomeron momentum. There may, however, be a statistical correlation of $x_{\mathbb{P}}$ and ξ_D. If the Pomerons do not fragment, then a measurement of the momenta of the scattered proton gives the mass of the produced Higgs boson. The cross section of this case, the so-called elastic part, has been evaluated in [14] in the framework of Regge theory and is found to be of the order of 0.1 pb, which is of the same order of magnitude as what we get for the total double diffractive case, including possible fragmentation of the Pomerons. This situation should be clarified.

In order to make more reliable predictions for hard diffractive scattering at pp colliders, the gluon content of the Pomeron has to be determined much more precisely. The present experimental analyses cover a range from about $Q = 3\,\mathrm{GeV}$ to $Q = 10\,\mathrm{GeV}$, whereas the factorization scales to be employed for pp collider physics reach up to 1 TeV. The gluon density at large scales is not very well constrained by the analysis of $F_2^{D(3)}$ at small scales, because it contributes in $\mathcal{O}(\alpha_s)$ only, and because of the large evolution span. Additional constraints by studying heavy quark and jet production at HERA and possibly at the Tevatron are needed to improve the situation.

The viability of the present study rests on the assumption that the simple factorization picture of eqs. (1) and (2) applies. The analysis of a toy model shows that the concept of factorization may break down for certain diffractive processes [23], and thus the expression of the cross section as a convolution of parton densities with a mass-factorized parton-level scattering cross section ceases to be valid in principle, although it may still be a good approximation in reality. This issue may be studied at present high-energy colliders. The pro-

[5] It is to be expected that the same argument applies also to the production of other systems with large invariant mass, such as jets and heavy quarks.

[6] The Pomeron remnants will be dragged towards the hard process because of the missing colour connection to the incident proton. However, this should not really influence the discussion, give or take one unit of rapidity.

[7] If the mass of the Higgs boson is assumed to be very small, of the order of 10 GeV, then it turns out that the $x_{\mathbb{P}}$ and β distributions are much broader, and that the pseudorapidity distribution of the Pomeron remnant jet extends to smaller values of η.

duction of heavy quarks or jets at large p_T in diffractive events in pp collisions is closely related to Higgs boson production studied in this paper, in the sense that the produced system has a large invariant mass and thus the momentum fractions probed in the proton and Pomeron are large. A comparison of the corresponding cross sections from the Tevatron with theoretical predictions would give a hint of what can be expected in the case of Higgs boson production at the LHC.

Finally, we wish to make some comments on the background to the process studied here. As said before, the idea is to exploit the fact that the Pomeron is a gluon-rich object, and thus background processes that are quark initiated should be suppressed. We briefly consider two cases. One is the decay of the Higgs boson into $\tau^+\tau^-$, proposed in [24]. It has been shown in [25] that there is an overwhelming background from $t\bar{t}$ production that renders this channel unfeasible. Unfortunately, $t\bar{t}$ production proceeds mainly via gg fusion, and so this background is expected to be large in the diffractive case as well. It might be the case, however, that the $t\bar{t}$ production cross section turns out to be smaller, because of the large invariant mass of the $t\bar{t}$ pair. The other case we wish to comment on is the decay $H \to \gamma\gamma$. As mentioned in the introduction, there are two types of backgrounds, the irreducible one from the production of photons via $q\bar{q}$, gg fusion and bremsstrahlung, and the reducible one, where jets fake photons. The latter background and the bremsstrahlung contribution can be reduced considerably by photon isolation cuts [26]. The direct production of photon pairs in $q\bar{q}$ and gg fusion has been studied in [27], where it has been shown that the $q\bar{q}$ process dominates. This background might thus be reduced in the case of diffractive events. It seems to be worth while to amend these qualitative remarks about the background by a thorough quantitative study[8].

To summarize: we have studied the production of the Standard Model Higgs boson at the LHC in single and double diffractive processes. Depending on the parametrization of the gluon content of the Pomeron, the production cross section for the single diffractive case may be sizeable and reach up to 25% of the total Higgs boson production cross section, if the Pomeron is gluon-dominated at large β for small scales. However, the present parametrizations for the gluon density of the Pomeron are not yet sufficiently precise to allow for a reliable prediction. Due to the large mass of the Higgs boson, the diffractive events studied in this paper have only a “small” rapidity gap between the leading proton and the Pomeron fragments, the latter having typically a very small transverse, but an extremely large longitudinal momentum. Besides a leading proton detected in a forward detector, the experimental signature will

[8] We would like to remark that an effective gluon density for hard diffractive processes may easily be implemented in existing programs by parametrizing the convolution integral in eq. (2), thus replacing a parton density by a fracture function.

be a comparably small hadronic activity in the forward direction.

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